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INTELLIGENT SYSTEMS FOR MANAGING ENERGY EFFICIENCY AND THERMAL SAFETY IN NEXT-GENERATION BUILDINGS

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Abstract

This article examines the role of intelligent management systems in improving the energy efficiency and thermal safety of next-generation buildings. The study explores the application of Artificial Intelligence (AI), the Internet of Things (IoT), Digital Twin technology, and smart monitoring tools in energy management processes. The findings indicate that these technologies contribute to optimizing energy consumption, enhancing the reliability of thermal systems, and reducing operational costs. The study further demonstrates that integrating energy efficiency and thermal safety within a unified digital management environment is a key approach to improving the operational performance and sustainability of modern buildings.

Keywords: Next-generation buildings, energy efficiency, thermal safety, intelligent management systems, Artificial Intelligence (AI), Internet of Things (IoT), Digital Twin, smart buildings, energy management, digital technologies.

Introduction

The construction industry is one of the key drivers of economic growth and technological advancement. Modern buildings are expected not only to ensure structural reliability and functional comfort but also to promote the efficient use of energy resources and guarantee safe operation throughout their service life [2;

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10]. Therefore, improving energy efficiency and thermal safety has become a strategic priority in the management of next-generation buildings.

Next-generation buildings are based on the integrated management of energy consumption, indoor environmental conditions, and engineering systems within a unified information environment [6]. This approach enables the optimization of energy use, enhances the reliability of technical equipment, and provides a comfortable and safe indoor environment for occupants [15].

The relevance of this research is largely associated with the fact that a significant share of building energy consumption is attributed to heating, ventilation, and air-conditioning (HVAC) systems [5]. The efficient operation of these systems plays a crucial role not only in reducing energy consumption but also in ensuring thermal safety and operational stability [11; 14]. Digital technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), Digital Twin technology, and smart sensors provide opportunities for real-time energy monitoring, load forecasting, and the assessment of engineering system performance [1; 4; 13].

Although various aspects of these technologies have been extensively investigated in the scientific literature, the integration of energy efficiency and thermal safety within a unified intelligent platform remains an important research challenge [6; 18]. In this context, intelligent management systems represent an effective tool for optimizing energy use, reducing operational costs, and improving the technical reliability of buildings [5; 20].

The purpose of this study is to analyze intelligent systems for managing the energy efficiency and thermal safety of next-generation buildings and to develop scientific and practical recommendations for their effective integration.

RESEARCH METHODOLOGY

This study investigates intelligent systems for managing the energy efficiency and thermal safety of next-generation buildings through a comprehensive research approach. The theoretical foundation of the study is based on scientific publications published between 2020 and 2025 focusing on Building Energy Management Systems (BEMS), Artificial Intelligence (AI), the Internet of Things (IoT), Digital Twin technologies, and smart building concepts [1–20].

The research methodology incorporates a systematic approach, comparative analysis, content analysis, and synthesis methods. Initially, the interrelationship

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between energy management and thermal safety was examined through a comprehensive review of the existing literature, and the functional capabilities of modern intelligent systems were assessed [2; 6; 10]. Subsequently, the roles of AI algorithms, IoT sensors, and Digital Twin technologies in energy monitoring, thermal load forecasting, and early fault detection were comparatively analyzed [4; 11; 13].

The analytical framework of the study was based on the relationships among energy consumption, data acquisition and processing, decision-making mechanisms, and thermal safety control processes. Within this framework, the impact of intelligent technologies on improving energy efficiency, reducing operational costs, and enhancing the reliability of engineering systems was evaluated [5; 14; 19]. Based on the synthesized findings, the integration of energy management and thermal safety into a unified digital platform was identified as a priority direction for ensuring the sustainable and efficient operation of next-generation buildings [17; 18; 20].

LITERATURE REVIEW

Ensuring the energy efficiency and thermal safety of next-generation buildings has emerged as an important research area resulting from the integration of construction engineering, energy technologies, and information systems. Reducing energy consumption, ensuring the reliable operation of engineering systems, and maintaining indoor environmental parameters within acceptable limits require the adoption of advanced management approaches [2; 10]. Consequently, the scientific literature increasingly treats energy management and thermal safety not as separate processes but as interrelated components of a unified intelligent building management system [6].

Early studies primarily focused on monitoring energy consumption and improving energy efficiency. Over time, however, the functional capabilities of energy management systems have expanded significantly. In particular, the development of Building Energy Management Systems (BEMS) has enabled the automation of energy monitoring, analysis, and control processes [2; 5]. Researchers emphasize that modern energy management systems can process large volumes of energy-related data to optimize energy use and reduce operational costs [7]. Nevertheless, achieving energy efficiency alone is insufficient; ensuring the safe and reliable operation of engineering systems has become equally important. As a result, the interrelationship between energy management and thermal safety has become a new focus of scientific investigation.

The introduction of Artificial Intelligence (AI) has played a crucial role in the advancement of this field. Numerous studies demonstrate that AI technologies are capable of analyzing energy consumption patterns, forecasting energy demand, and generating optimal management decisions [1; 11]. In particular, machine learning algorithms make it possible to predict fluctuations in energy demand and adapt the operating modes of engineering systems accordingly [11; 16]. As a result, the efficiency of energy resource utilization is improved while the risk of system overload is reduced. This also creates favorable conditions for maintaining thermal safety within buildings.

Since the effectiveness of AI-based systems largely depends on the availability and accuracy of data, Internet of Things (IoT) technologies have become an essential component of intelligent energy management systems [13]. Smart sensors continuously monitor indoor temperature, humidity, energy consumption, equipment conditions, and other operational parameters [17]. These data are processed in real time and transmitted to management platforms. Researchers note that IoT technologies improve the accuracy of energy monitoring, facilitate early fault detection, and support the uninterrupted operation of engineering systems [13; 17]. Consequently, energy efficiency and thermal safety management processes are integrated into a unified information environment.

Among the technologies designed to enhance both energy efficiency and thermal safety, Digital Twin technology has attracted considerable attention as a promising solution [4]. This technology establishes continuous information exchange between a physical building and its virtual representation. Through the virtual model, energy flows, thermal loads, and equipment conditions can be continuously analyzed, while potential failures can be predicted in advance [3; 4]. This improves the accuracy of management decisions, reduces energy losses, and enhances safety performance. Therefore, many researchers consider Digital Twin technology one of the most effective tools for integrating energy management and thermal safety functions within intelligent buildings [4].

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The concept of thermal safety has also evolved considerably in recent years. Initially associated mainly with the safe operation of heating systems, it is now understood more broadly to include maintaining indoor environmental quality, ensuring the reliability of engineering systems, and preventing energy losses [11; 14]. Research findings indicate that deficiencies in energy management often negatively affect thermal safety, while failures in thermal systems frequently result in increased energy consumption [14; 20]. These observations confirm the necessity of treating energy efficiency and thermal safety as a unified management objective.

The development of these scientific perspectives has led to the emergence of the Smart Building concept. Within this framework, energy efficiency, safety, comfort, and sustainability are integrated into a single management platform [6; 10]. Smart buildings rely on the coordinated operation of sensors, AI algorithms, automated control systems, and digital platforms [6]. This integration contributes to optimized energy consumption, enhanced operational reliability, and improved management performance [15].

Recent studies have further linked this approach to the principles of Industry 5.0. Unlike previous industrial paradigms focused primarily on productivity and efficiency, Industry 5.0 emphasizes human well-being, environmental sustainability, and responsible resource utilization [18]. From this perspective, the integrated management of energy efficiency and thermal safety is considered a fundamental functional requirement of next-generation buildings.

International experience demonstrates that the implementation of AI, IoT, Digital Twin technologies, and intelligent energy management systems has enabled many developed countries to reduce energy consumption, optimize operational costs, and improve thermal safety performance [5; 10; 19]. At the same time, the literature reveals a lack of universal methodological approaches capable of comprehensively evaluating both energy efficiency and thermal safety within a unified framework. This gap highlights the need for further research aimed at improving intelligent management systems for next-generation buildings and developing comprehensive methods for assessing their effectiveness [11; 19; 20].

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ANALYSIS AND RESULTS

Ensuring energy efficiency and thermal safety in next-generation buildings is closely related to the rational use of energy resources, the reduction of operational costs, and the provision of continuous and safe building operation. The literature review indicates that a significant share of energy consumption in buildings is associated with heating, ventilation, and air-conditioning (HVAC) systems [2; 5]. Therefore, considering energy management and thermal safety as a unified management system has become an important direction in the development of next-generation buildings [6].

The analysis shows that in traditional management systems, energy consumption indicators are mainly monitored periodically, and management decisions are often based on the experience of operators [2]. In contrast, intelligent management systems employ sensors, data-processing algorithms, and artificial intelligence technologies to monitor energy consumption in real time and generate automated management decisions [1; 13]. This approach makes it possible to reduce energy losses and improve the operational efficiency of engineering systems [5].

Table 1 Comparative Characteristics of Traditional and Intelligent Energy Management Systems.[1]

Indicator	Traditional System	Intelligent System
Monitoring Method	Periodic monitoring	Real-time monitoring
Data Processing	Manual	Automated
Decision-Making	Operator-based	AI-driven
Energy Consumption Forecasting	Not available	Available
Fault Detection	Delayed detection	Early detection
Thermal Safety Control	Limited	Continuous

The data presented in Table 1 demonstrate the advantages of intelligent systems in improving energy efficiency and ensuring thermal safety. In particular, the capability of real-time data processing enables the rapid identification of factors contributing to increased energy consumption and supports the implementation of timely corrective measures [7].

[1] Manba: xalqaro tadqiqotlar asosida muallif tomonidan tuzildi.

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IoT technologies play a significant role in enhancing the effectiveness of energy management systems. IoT sensors continuously collect information on indoor temperature, humidity, energy consumption, and the technical condition of building equipment [13; 17]. These data are transmitted to a centralized platform and processed using artificial intelligence algorithms [1]. As a result, opportunities are created for optimizing energy consumption and thermal loads within the building.

Table 2 Functions of IoT and Artificial Intelligence Technologies in Energy Management.[2]

Technology	Main Function	Expected Outcome
IoT Sensors	Data collection	Continuous monitoring
Big Data Platforms	Data storage and processing	Improved analytical accuracy
Artificial Intelligence	Forecasting and optimization	Reduced energy consumption
Machine Learning	Demand prediction	More efficient resource utilization
Automated Control Systems	Decision implementation	Operational efficiency and rapid response

The advantages of intelligent technologies are also clearly evident in the management of thermal safety. According to research findings, the timely detection of faults in heating and ventilation systems not only prevents energy losses but also reduces technical risks and operational hazards [14; 20]. For this reason, thermal safety management in modern buildings is increasingly organized in integration with energy monitoring systems [11].

In this context, Digital Twin technology plays a particularly important role. Through Digital Twin technology, a virtual model of a building is created, enabling all engineering systems to be monitored in real time [4]. This technology provides opportunities to predict energy consumption, thermal loads, and equipment conditions. Studies indicate that the implementation of Digital Twin technology improves the accuracy of management decisions and contributes to reducing energy losses [3; 4].

[2] Manba: muallif tomonidan xalqaro manbalar asosida tuzildi

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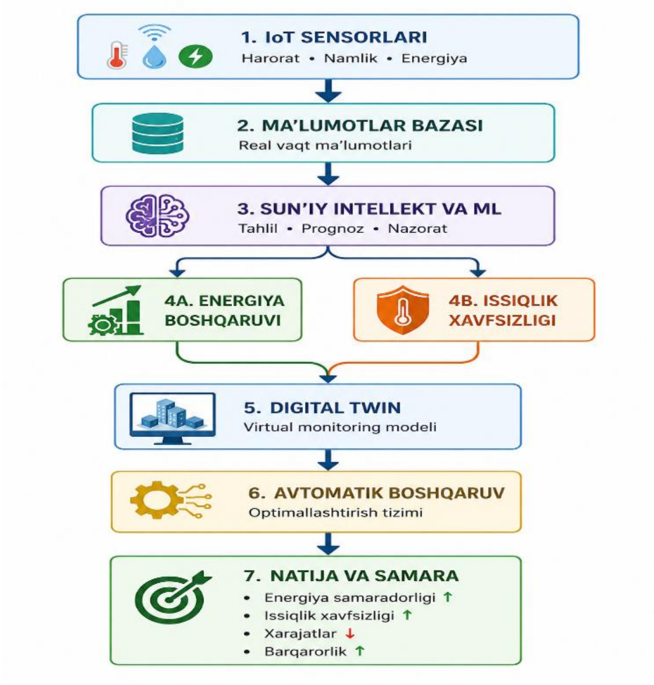

Figure 1. Model for Managing Energy Efficiency and Thermal Safety in Next-Generation Buildings.[3]

The analysis indicates that managing energy efficiency and thermal safety through a unified digital management platform, rather than addressing them separately, yields superior outcomes [6; 18]. Such an integrated approach enables the optimization of energy consumption, extends the service life of engineering equipment, and reduces operational costs [5; 19].

Table 3 Benefits Achieved Through the Implementation of Intelligent Systems.[4]

Area	Outcome
Energy Consumption	Reduced
Thermal Safety	Improved
Monitoring Quality	Enhanced
Fault Detection	Accelerated
Operational Costs	Decreased
Management Efficiency	Increased

[3]Manba: muallif ishlanmasi
[4] Manba: xalqaro amaliyot va ilmiy tadqiqotlar asosida tuzildi

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The obtained results indicate that the most promising approach to managing energy efficiency and thermal safety in next-generation buildings is the integration of Artificial Intelligence (AI), the Internet of Things (IoT), Digital Twin technology, and automated control systems within a unified information environment [4; 17; 20]. Such an approach not only improves the efficiency of energy resource utilization but also contributes to the safe, sustainable, and economically efficient operation of buildings [1; 18].

CONCLUSIONS AND RECOMMENDATIONS

The results of this study demonstrate that energy efficiency and thermal safety in next-generation buildings are closely interconnected and should be considered as complementary components of a unified management framework. The literature review and analytical findings confirm that the efficient utilization of energy resources, the reliable operation of engineering systems, and the maintenance of indoor environmental quality are directly associated with the application of advanced intelligent management technologies [2; 10; 11].

The analysis revealed that intelligent management platforms are considerably more effective than traditional management systems in monitoring energy consumption, forecasting energy demand, and ensuring thermal safety [1; 5]. In particular, the collection of real-time data through IoT sensors, the processing of information using artificial intelligence algorithms, and the application of Digital Twin technology for decision-making contribute significantly to optimizing energy consumption and improving the reliability of engineering systems [4; 13; 17].

The study further found that integrating energy efficiency and thermal safety within a unified digital management environment represents the most effective approach for next-generation buildings [6; 18]. Such integration facilitates the reduction of energy consumption, supports early fault detection, extends the service life of equipment, and optimizes operational costs [14; 19].

Based on these findings, it is recommended to integrate energy management systems with IoT sensor networks, apply artificial intelligence algorithms for energy consumption forecasting, and implement Digital Twin technologies for monitoring and controlling the operational condition of engineering systems in next-generation buildings [4; 11; 17]. Furthermore, the development of a unified system of indicators for assessing energy efficiency and thermal safety, together with a higher degree of process automation, is recommended to improve overall building performance [7; 19].

In general, intelligent systems for managing energy efficiency and thermal safety play a vital role in ensuring the sustainable, safe, and economically efficient operation of next-generation buildings. The wider adoption of these technologies can significantly contribute to the rational use of energy resources, the reduction of operational expenditures, and the enhancement of overall building management effectiveness [5; 18; 20].

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